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Can Water Allocation in the Yellow River Basin Be Improved?

Insights from a Multi-Agent System Model

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ABSTRACT

In 1999, the Government of China enforced a cross-provincial, quota-based Water Allocation Agreement that was developed in 1987 and titled Unified Water Flow Regulation (UWFR) to ensure that flow to the Yellow River mouth would not be cut off. This policy was in line with the refocus of the Government, over the last decade, on sustainable water use and keeping the Yellow River healthy. The policy enforcement ended more than two decades of flow-cutoffs, that is, periods when the Yellow River did not reach the Bohai Sea at its mouth, during an increasing number of days every year. While the UWFR was an important step forward in protecting the water resources in Northern China, the allocation did not take into account the value of water in various uses and water users who had to give up water resources, chiefly irrigators in the upstream and midstream provinces were not compensated. Could alternative water management options have brought about a better outcome for irrigators and the downstream ecosystem? We analyze this question using a Multi-Agent System (MAS) modeling framework for the Yellow River Basin (YRB). We find that compared to the baseline scenario simulating UWFR management, water trading among irrigation districts would result in a small decline in water consumption, a significant increase in agricultural GDP, and a small increase in total basin GDP. Overall GDP increase would be much higher if domestic and industrial uses became active water trading sectors.

Keywords: water allocation, river basin management, multi-agent system, optimization, Yellow River

ACKNOWLEDGMENTS

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ABBREVIATIONS AND ACRONYMS

UWFR	Unified Water Flow Regulation
MAS	multi-agent system
YRB	Yellow River Basin
GDP	gross domestic product
EA	ecosystem agents
YRCC	Yellow River Conservancy Commission
M&I	municipal and industrial
RMSE	root mean square error

1. INTRODUCTION

The management of the Yellow River Basin (YRB) is critical for China's agricultural production and socioeconomic development. The cultivated area in the basin is about 13 percent of total cultivated area in China, but the basin holds only 3 percent of the country's water resources. At the same time, the basin provides domestic supplies to an estimated 150 million people, both inside and outside the basin area, as well as to rapidly growing industries, both in the downstream area and, more recently, in the midstream area, where mining and chemical industries are rapidly expanding. As a result, the basin faces severe water shortages. Given the extreme water shortages in the basin, how can water resources be managed to continue to support agricultural and economic development while also improving outcomes for the environment?

In the past, increasing the supply of water through new water development has been a common strategy to manage water resources. However, in maturing water economies, such as the YRB, the focus is increasingly shifting to demand management to generate both physical savings of water and economic savings by increasing the output per unit of evaporative loss of water, by reducing water pollution, and by reducing non-beneficial water uses (Randall 1981). Many studies have focused on various aspects of demand management to reduce water shortages in the basin, such as water rights (Wang et al. 2008, Shao et al. 2009, Zhao et al. 2009) and water prices (Huang et al. 2006, Wang et al. 2008). Since 2000, the Government of China has promoted the establishment of water rights systems by conducting demonstration projects in the YRB aimed at reducing water competition among sectors. The purpose of these demonstration sites is to reallocate water from agriculture to industry by increasing irrigation efficiency, generally through engineering measures, such as canal lining. One transfer pilot project operates in Ningxia Province, and 16 projects signed transfer contracts in Inner Mongolia, with a value of US$100 million. Under these projects, irrigation districts transfer part of their water-use rights to industrial enterprises for a period of 25 years. However, analyses showed that water users in the irrigation districts are generally not aware of the water rights transfer; transfers are determined by the administration, not markets; and there are no adjustments based on market signals or economic measures. Thus, major challenges remain until a true market for water rights can be established (Ringler et al. 2010).

The intra-provincial irrigation-to-agriculture transfers in the YRB provide important insights for the potential development of inter-provincial water trading, which has been discussed by both policymakers and water allocation managers at the Ministry of Water Resources and the Yellow River Conservancy Commission (YRCC) for several years. Such a reallocation could potentially increase the water allocation efficiency of the 1987 cross-provincial water allocation agreement. However, relatively water-abundant upstream provinces have a strong interest in maintaining the status quo in water allocation. Moreover, given the large share of return flows in the YRB, changes in provincial permits from upstream to downstream might be inconsequential. It is therefore important to assess the full costs and benefits of changing the current system of water quotas. Heaney et al. (2005) assess the benefits of water reallocation across YRB water resource regions using a production function approach without accounting for the river hydrology (flow routing or return flows). They estimate economic benefits through increased value of agricultural production at 1 billion RMB per year, with reallocation chiefly occurring from the midstream to the downstream area.

The purpose of this paper is to study water rights trading across all sectors and within an integrated economic-hydrologic modeling framework using a multi-agent system developed by Yang et al. (2010) for the YRB. Thus, this paper focuses on results and insights for water allocation in the YRB while Yang et al. focused on the modeling method. The following sections introduce the model used for the analysis, describe the scenarios analyzed, present the results, and conclude with a series of final remarks.

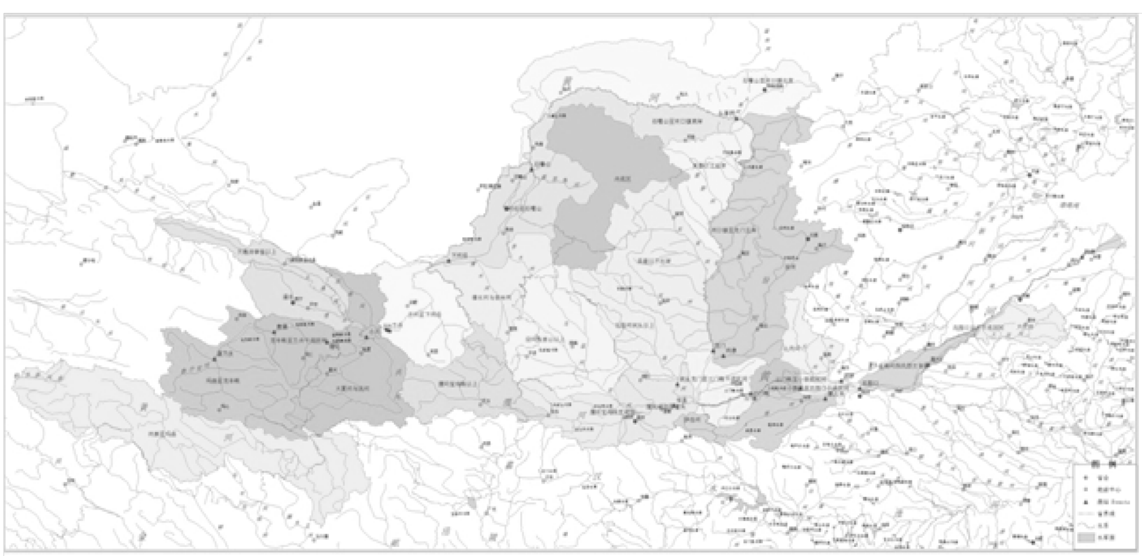
2. MODEL SPECIFICATION FOR THE YELLOW RIVER BASIN

Traditionally, to address issues of water resource allocation, the entire basin was modeled as a single system, with water use of individual water users (agents) as a decision variable in a consistent mathematical programming model that optimizes system-level objectives. However, in real-world situations, individual agents can make decisions that would maximize personal profits but not necessarily confer basin or system-wide benefits. Thus, the number of decision variables can quickly become too large, rendering the model unsolvable. The situation is even more complex if the utility function is nonlinear. In order to reduce computational difficulty while still reflecting real-world water allocation institutions, we apply a Multi-Agent System (MAS) developed by Yang et al. (2010) to analyze the water allocation problem of the YRB.

The theory of MAS has emerged from computer science theories associated with distributed artificial intelligence (Sycara 1998). An agent is defined as an autonomous unit within a system that interacts with others and is characterized by behavioral rules. In a watershed MAS, agents can be defined as water users that utilize water for their own benefits (Yang et al., 2009). The water use decisions of the agent are affected by the behavior of its neighbors, and are limited by both physical conditions and management regulations. The MAS model depicts water management institutions more realistically than does a conventional centralized model, which assumes an omniscient decision maker controlling not only system-level decisions but also the decisions of individual water users or stakeholders. The definitions of agents are briefly described as follows.

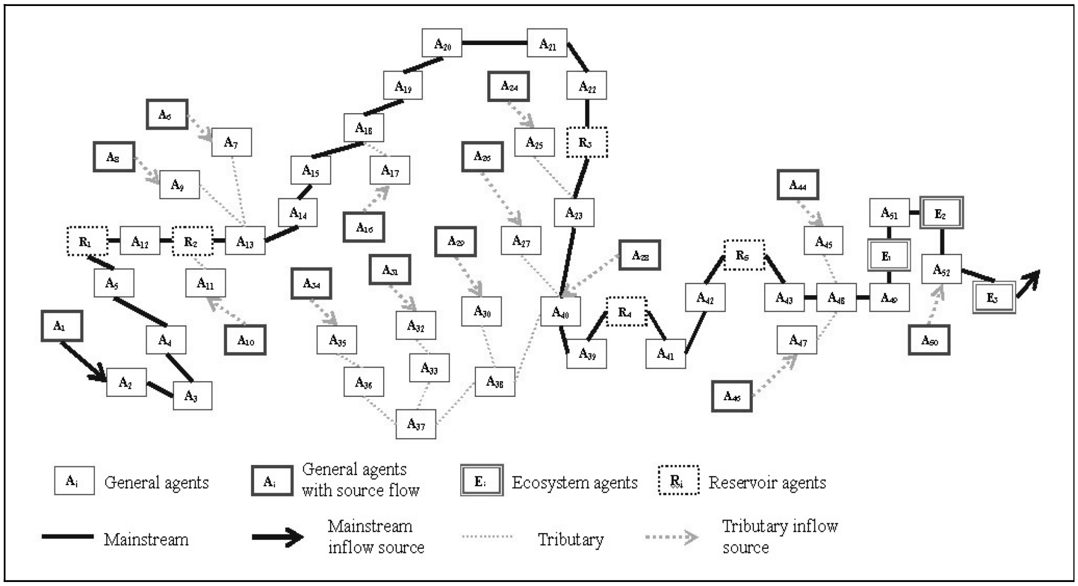
Zhao et al. (2009) used the border of provinces and the boundary of natural sub-basins or watersheds to decompose the entire YRB into a number of *hydro-economic units*, or agents (Figure 2.1a). For each of these units we estimated the values of local surface inflows, which consider local overland flow and evaporation. The amount of groundwater supply was also assessed and treated as a local *reservoir* in each unit. Local surface inflow, groundwater supply, and upstream inflows were treated as total available water for each unit. Water utilization was separated into agricultural and municipal and industrial (M&I) use. Hydropower stations were included as separate additional agents, as were minimum environmental flows at downstream stations. Water use data for each category of water use and the corresponding gross domestic product (GDP) were also summarized for each of the hydro-economic units. Based on these data, a total of 52 units were identified and defined as *agents* (Figure 2.1b).

Figure 2.1a—Hydro-economic units, Yellow River Basin



Source: Authors.

Figure 2.1b—Agent map of the Yellow River Basin- 52 general agents, 5 reservoir agents and 3 ecosystem agents



Source: Zhao et al. (2009).

Agents are characterized by water availability, water use, and associated benefit functions. Benefit functions for M&I and agricultural water use were developed based on the relationship between GDP and water use by sector. Details are presented in Yang et al. (2010).

More than 3,000 reservoirs are located in the YRB. Their total storage is approximately 70 km^3, which exceeds the total annual runoff of the river of 58 km^3 (Cai and Rosegrant 2004). It is impossible (and not necessary) to identify all the reservoirs as agents in this study, because most of them are small and their capacity is not sufficient to carry over water across the minimum time period of the model (that is, a month). Therefore, only the five key reservoirs were included as separate agents. They are, from upstream to downstream, Longyangxia, Liujiaxia, Wanjiazhai, Sanmenxia, and Xiaolangdi. The combined storage for these reservoirs is about 51 km^3. The selected reservoirs are all multipurpose for water supply, flood control, and hydropower generation. As a result, their operation rules are highly complex. Incorporating the real operation rules of each reservoir into the modeling is beyond the scope of this study. To simplify the model without misrepresenting this complex system, the reservoir agents are characterized by two behavior rules, 1) they follow their predetermined operation curve to regulate streamflow, and 2) they maximize hydropower generation.

Three ecosystem agents are defined near the river mouth as reflecting important ecological and environmental concerns in the lower basin area. Ecological and environmental flow requirements have been assessed by local scientists (for example, Ni et al. 2002, Yang et al. 2009, Cui et al. 2009, and Liu et al. 2009). They considered different environmental functions of the streamflow and defined environmental flow requirements for high-flow (July to October) and low-flow (November to June) periods. The results of Ni et al. (2002) and Yang et al. (2009) are used to set up the target flow for two ecosystem agents: Huayuankou and Gaocun. Water demands of a third ecosystem agent, Lijin, at the delta of the Yellow River, have been assessed by Cui et al. (2009) and Liu et al. (2009). Cui et al. (2009) separated a fish breeding period (April to June) from the reminder of the low-flow period. Liu et al. (2009) defined total ecological water requirements with consideration for wetland plants, freshwater fish communities, and the bayou ecosystem. We adapt the flow requirements of Cui et al. (2009) for this study. Flow targets for all ecosystem agents in different time periods are provided in Table 2.1. Table 2.1 also provides a second, higher set of instream flow targets needed for sediment flushing. These were not used, however, as they would prohibit much off-stream activity.

Table 2.1—Target instream flow for ecosystem agents (EA) in different periods (without/with considering sediment flushing) (billion m^3/month)

Agents	Normal flow period (November–March)	Fish breeding period (April–June)	High-flow period (July–October)
EA_1 (Huayuankou)	0.341/0.605	0.341/0.605	0.455/5.111
EA_2 (Gaocun)	0.277/0.612	0.277/0.612	0.397/6.016
EA_3 (Lijin)	0.363/0.363	2.581/2.581	0.850/15.85

Source: Collected from various references for this study.
Note: EA = Ecosystem Agent. The subscript 1, 2, and 3 refer to the respective locations.

3. SCENARIO DEFINITIONS

Three different scenarios are used in this study to evaluate the consequences of different water management mechanisms for the YRB:

1. the de facto water allocation plan (baseline),
2. unmanaged water allocation (without basin-wide regulation prior to 1999), and
3. market-based water allocation

This section describes these scenarios, as well as their implementation through the various agents (Table 3.1).

Table 3.1—Agent settings across scenarios

	UWFR	Unmanaged	Water Trading
General agents	Water consumption is limited by physical constraints and water rights	Water consumption is only limited by physical constraints	Water consumption is limited by physical constraints, can surpass water rights through trade
Reservoir agents	Minimizing the difference between actual and target water release	Maximizing the product of water release and water head	Inactive
Ecosystem agents	Inactive	Inactive	Inactive, but using UWFR results as flow requirement

Source: Authors.
Note: UWFR stands for Unified Water Flow Regulation.

Baseline Scenario (UWFR)

During 1972–1998, Yellow River streamflow did not reach the river mouth several days of the year, causing serious socioeconomic and environmental problems in the downstream area, and raising concerns in the Chinese government and internationally. To address this problem, the Yellow River Conservancy Commission (YRCC), authorized by the State Council of China, implemented the Unified Water Flow Regulation (UWFR) in the YRB. The UWFR is based on a 1987 Agreement on water quotas across the riparian provinces in the basin (see Table 3.2). The Agreement allocates a total of 37 km^3 across the riparian provinces, including 2 km^3 to downstream urban-industrial centers outside the basin area, out of a total runoff of 58 km^3. The UWFR scenario ensures that flows reach all downstream ecosystem agents throughout the year.

Table 3.2—Water allocation agreement of 1987

Province	Water withdrawal (billion m^3)	Province	Water withdrawal (billion m^3)
Qinghai	1.41	Shaanxi	3.80
Sichuan	0.04	Shanxi	4.31
Gansu	3.04	Henan	5.54
Ningxia	4.00	Shandong	7.00
Inner Mongolia	5.86	Hebei/Tianjin	2.00

Source: Zhao et al. 2009.

Under the UWFR, YRCC issues water release targets for each reservoir every month, considering the current reservoir storage, future weather forecasts, and downstream water demand. This study assumes that the objective for each reservoir is to match the suggested release issued by YRCC under the UWFR, based on actual monthly water releases in 2000, which have been used for calibration. However, it should be noted that YRB reservoir operations are highly complex due to the multiple functions of each of the reservoirs; as a result, reservoir managers may not exactly follow the instructions from YRCC.

Scenario without Regulation

The scenario without regulation assumes no management regulation. As a result, the agents are free to use all available water supplies to meet demands. The only constraint that will affect their decision is the physical limitation of water availability. An obvious result from this scenario is that upstream water users will take advantage of available water while downstream water users can only utilize whatever is left from upstream. In addition, the objectives of reservoir agents are no longer constrained by the prescribed release targets under the UWFR. Instead, reservoir agents try to maximize hydropower generation. The main purpose of the UWFR is to avoid flow cutoffs in the downstream channel. When no regulation is enforced, it is expected that flows will be cut off at downstream reaches under this scenario.

Water Trading Scenario

The baseline scenario (UWFR) assumes that all agents will follow the water quota agreement. In other words, actual water consumption (x_i) for each agent will be less or equal to the water rights (w_i) assigned under the UWFR. In the water trading scenario, on the other hand, water depletion can be higher or lower based on the volume of water traded. In particular, agricultural agents can trade water across the entire system. Municipal and industrial (M&I) agents are not active traders, because their demands are met following priority allocation. Under this market-based setting, water trading is allowed between upstream and downstream agents. The general convergence criterion is that total water use must equal total water rights. The initial water entitlements are the same as those under the UWFR scenario. In a true water market, sales and purchases would need to match, but under this scenario, a quasi-market is assumed, where the government steps in to purchase excess water.

The market-based allocation mechanism is formulated to solve the water allocation problem. Without any centralized controls, an equilibrium condition can only be achieved by setting a convergence criterion. We do this through the price bargaining process, where local water prices are adjusted to ensure that the system-wide total water consumption equals total water rights. The equilibrium is reached when no agent in the system buys or sells additional water, after reaching the maximum marginal benefit through the price bargaining process.

In this scenario, allowing water transactions for the entire system means reservoir operation would become even more complex than for the previous two scenarios. Because the purpose of this scenario is to compare the impact of water use agents' decisions with the baseline, we render reservoir agents inactive for simplification. Using the monthly storage from the results of UWFR as targets, the reservoir agents under this scenario are set to match these target storages. If upstream inflow to the reservoir increases, reservoir releases increase proportionally, and vice versa. This setting allows water to move from upstream to downstream areas and water transaction to occur freely without reservoir economic constraints.

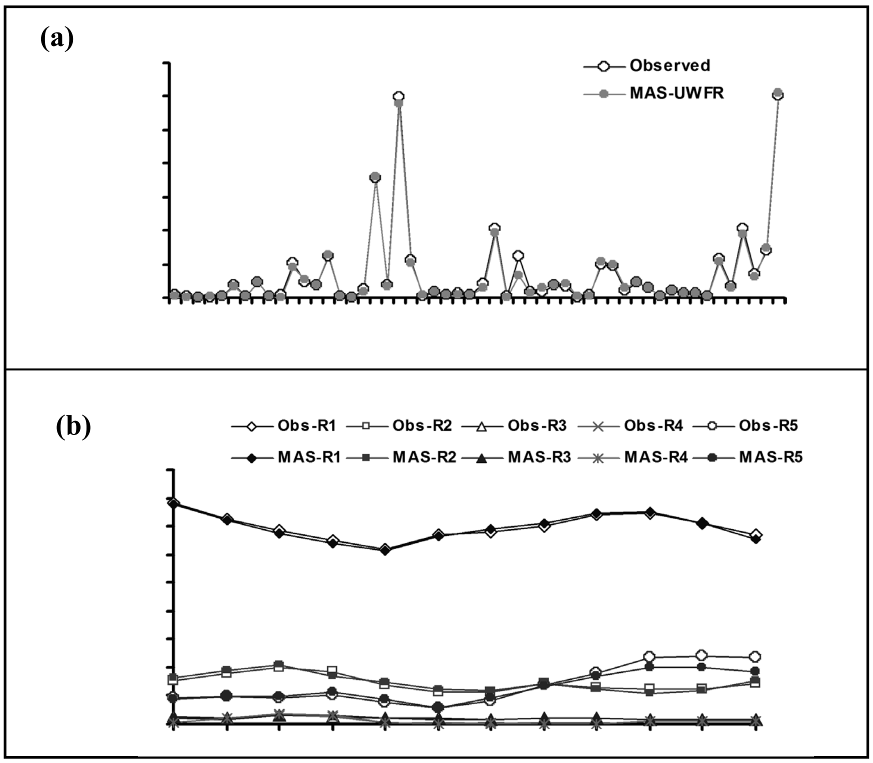
Ecosystem agents are also rendered inactive under the UWFR scenario. However, because no water benefit functions have been established for ecosystem agents, ecosystem benefits would be sacrificed under the water trading scenario. To ensure continued ecosystem flows, a constraint is placed on the agents located just upstream of the three ecosystem agents to ensure that their outflows match UWFR requirements. This is implemented by introducing a constraint to the local water price bargaining process, when UWFR requirements at the ecosystem nodes are not met. Because achieving the required downstream ecosystem flows will affect all upstream agents, the responsibility to maintain a certain level of stream flow for ecosystems is shared by all upstream agents.

4. RESULTS

Unified Water Flow Regulation (UWFR) Baseline Scenario

The Multi-Agent System (MAS) model is calibrated to the UWFR in 2000. In particular, flows are calibrated to: 1) the annual water consumption of all water use agents, 2) the monthly reservoir storage of all reservoir agents, and 3) the monthly streamflow at key gauges along the main channel and major tributaries. Results for water consumption and reservoir storage are provided in Figure 4.1.

Figure 4.1—The calibration result (a) agent's annual water consumption; (b) reservoir storage (billion m^3)



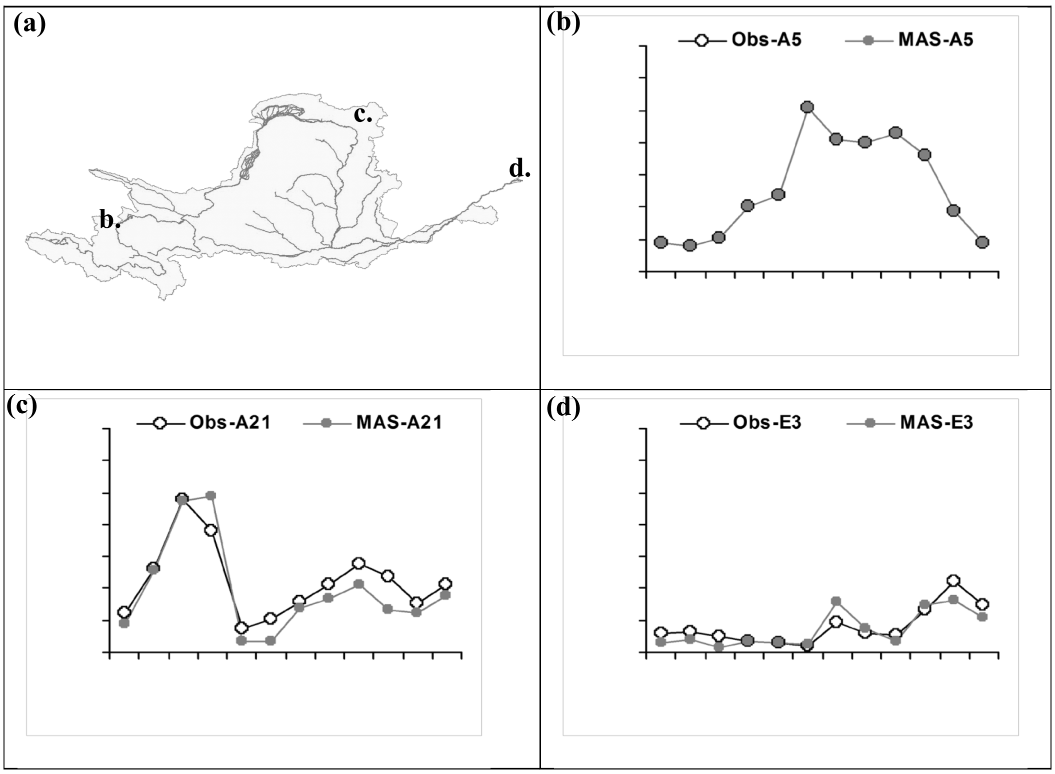
Source: This study.

Figure 4.1a plots the observed agent water consumption versus the modeled results. The observed annual total water consumption is 35.7 billion m^3 and the modeled result is 34.5 billion m^3, with a root mean square error (RMSE) of 0.106 billion m^3, or less than 1 percent of the total annual water consumption. Although there is a slight underestimation at the system level, the modeled water consumption patterns at the agent level matches well with observed values. Figure 4.1b presents a comparison for reservoir storage with similar calibration results for all the modeled reservoirs. The RMSEs for the five reservoirs—Longyangxia, Liujiaxia, Wanjiazhai, Sanmenxia, and Xiaolangdi—are 0.169, 0.175, 0.055, 0.033, and 0.448 billion m^3, respectively.

To evaluate calibration to 2000 streamflows, Figure 4.2 presents results for three flow-gauging stations located upstream, midstream, and downstream, respectively, as can be seen in Figure 4.2a. Figure 4.2b presents the result for Tangnaigai station. Because water consumption upstream is relatively low compared to streamflows, the streamflow result shows a perfect match with observed data. Figure 4.2c presents results for the midstream Toudaoguai station. Here, the modeled result shows a slight underestimate of streamflows after June; however, the annual flow pattern is very similar. Finally, Figure

4.2d presents the results for Lijin station, which is the most downstream flow-gauging station in the basin. Underestimation exists in the non-flood period (November to March), but the overall pattern is still captured well by the model. The RMSEs for these three stations—Tangnaigai, Toudaoguai, and Lijin—are 0.003, 0.282, and 0.160 billion m^3, respectively.

Figure 4.2—The calibration result of streamflow (a) gauge station locations; (b) upstream result—Tangnaigai station; (c) midstream result—Toudaoguai Station; (d) downstream result—Lijin Station



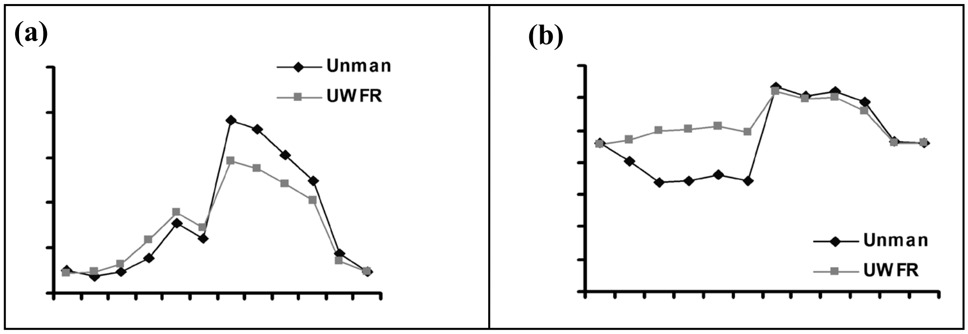
Source: This study.

Although the modeled results do not fully match the observations, the monthly pattern at the system level and the spatial patterns at the agent level all show a similar tendency, and RMSE values are at an acceptable range. Based on these calibration results, it is assumed that the MAS model can represent the current water usage condition reasonably well, and this calibrated model is used for additional scenario analyses.

Scenario without Regulation

The scenario without regulation mimics the situation before the UWFR was implemented, where agents can use as much water as they want up to the physical water availability limit. All other parameters and settings are identical with the UWFR scenario. The results are given in Figure 4.3.

Figure 4.3—System-wide comparison between the UWFR scenario (baseline) and the unmanaged water scenario (a) monthly water consumption (billion m3); (b) monthly GDP (billion RMB; 1 RMB = approximately US$0.146)

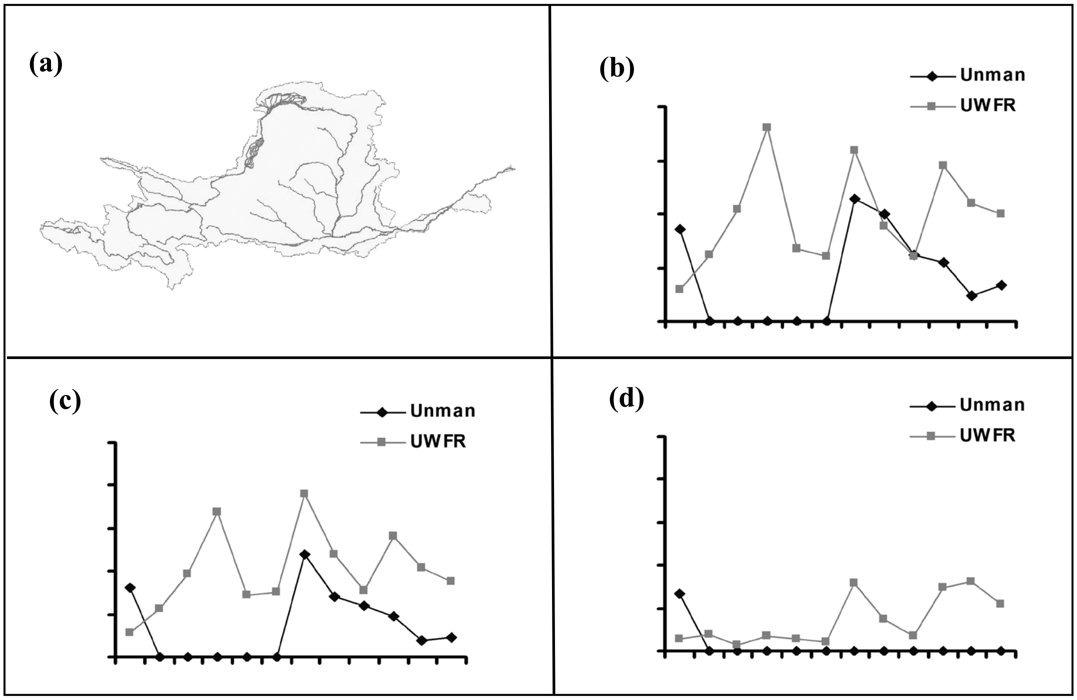


Source: This study.

As can be seen from Figure 4.3a, under the unmanaged scenario, water consumption increases during the high-flow period (July to October) and decreases in the low-flow period. This is due to the larger water flows that can be depleted under first-come-first-serve (unregulated) flow allocation, whereas under the low-flow period, UWFR consumption levels are higher due to the larger reservoir storage and thus flow regulation capability under UWFR. One exception is water consumption in the low-flow month of January, which is larger under the unregulated flow scenario. This is because the reservoir storage for the first month is sufficiently large to sustain a higher water consumption level. However, less water is released from the reservoirs during February to June, which results in a decline in water availability for downstream water use agents. Basin gross domestic product (GDP) reflects the monthly patterns of water consumption (Figure 4.3b). The decline in water consumption of about 2 billion m^3 per month during February to June results in an average basin GDP decline of 40 billion RMB per month. On the other hand, the water consumption increases from July to October result in a slight increase in GDP. Annual water consumption under the scenario without regulation is 38.3 billion m^3, 11 percent higher than the 34.5 billion m^3 under the UWFR scenario. The basin-wide GDP is 1123.26 billion RMB under the scenario without regulation, 10 percent less than the 1246.68 billion RMB under the UWFR scenario.

The downstream ecosystem is adversely affected under this scenario, as is shown in Figure 4.4. Figure 4.4a indicates the location of the three ecosystem agents. Figure 4.4b presents the result for ecosystem agent 1 (EA1), identified as Huayuankou. Flow cutoff events occur from February to June under the unmanaged scenario. Monthly flows average 0.389 billion m^3 for the scenario without regulation and 0.972 billion m^3 for the UWFR scenario. The flow difference and cutoff periods are even larger for ecosystem agents closer to the river mouth (Figures 4.4c and 4.4d).

Figure 4.4—Ecosystem agent comparison between the UWFR scenario (baseline) and the unmanaged scenario (a) ecosystem agents' locations; (b) result for ecosystem agent 1—Huayuankou; (c) result for ecosystem agent 2—Gaocun; (d) result for ecosystem agent 3—Lijin (billion m^3)



Source: This study.

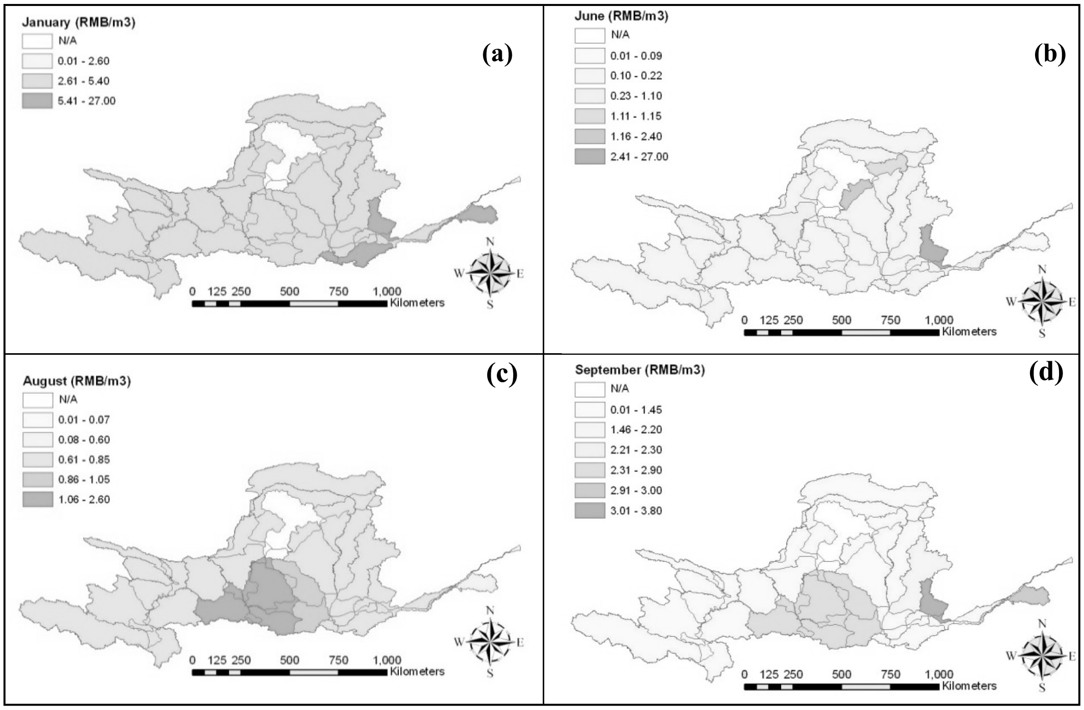
Figure 4.4c shows the result at Gaocun station, where ecosystem agent 2 (EA2) is located. The flow cutoff period is the same as for Huayuankou, and average monthly streamflow declines from 1.016 billion m^3 under the baseline scenario to 0.350 billion m^3 under the unmanaged flow scenario. Flow impacts are strongest for the most downstream ecosystem agent 3 (EA3) in the delta area (Figure 4.4d), where cutoff periods start in February and continue through December. Average flows drop from 0.358 billion m^3 to 0.051 billion m^3. These results reflect the period from 1972 to 1998, when the UWFR was not yet enforced.

These results show the benefit of the UWFR for downstream ecosystem flows. The annual average streamflow for ecosystem agents increases three to six times, and no flow cutoff events occur. This result matches the real-world situation—no flow cutoff events have been recorded since 1999, when the UWFR started to be enforced. Moreover, basin water consumption under the UWFR scenario is lower and GDP higher compared to the unmanaged scenario. Although some upstream agents experience declines in GDP—upstream GDP declines by about 2.5 billion RMB annually—basin-wide GDP is higher.

Water Trading Scenario

The water trading scenario starts from an initial water price of 27 RMB/m^3, a value estimated based on a series of model simulations. If the local water price is above this value, all agents would only use water for municipal and industrial (M&I) use and sell the rest of their water entitlement. This implies that the maximum marginal benefit of agricultural water use over the entire basin is 27 RMB/m^3. Starting from this initial water price, the model ends with equilibrium water prices for each agent and month. Results for selected months are shown in Figure 4.5.

Figure 4.5—Equilibrium water prices for different agents in different months (a) January; (b) June; (c) August; (d) September

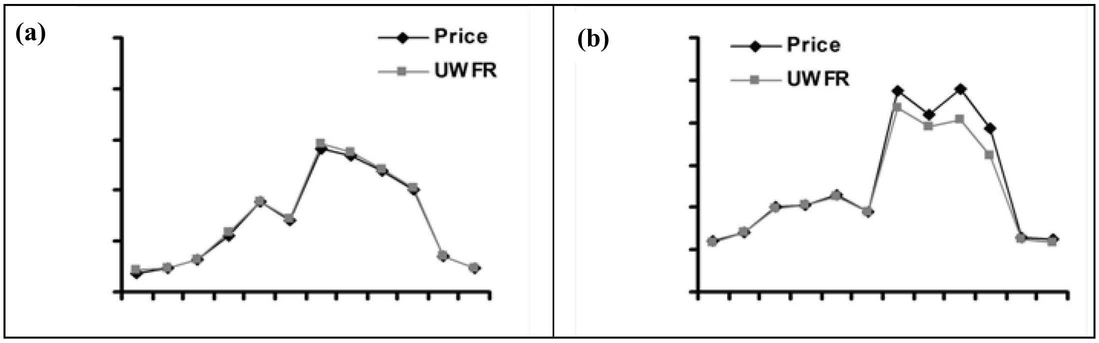


Source: This study.

Generally, water prices are higher in tributaries than in the mainstream because much less water is available and can be transferred. January is an example of a month with relatively uniform water prices for agents along the mainstream and the major tributaries. Only a few agents located at smaller tributaries in the downstream area show higher water prices (Figure 4.5a). Moreover, because January is usually the month with the lowest flow, the average water price for the entire system is relatively high compared to other months. In general, water prices are lower in high-flow months. However, spatial heterogeneity in water prices is a reality even in the high-flow season. Moreover, water prices in tributaries, particularly the source areas of tributaries, are higher than those in other places. This is because water transactions from the mainstream toward tributaries or from downstream toward upstream areas are physically impossible without engineering works. The marginal benefit of water in those areas will therefore be higher under the water trading scenario. The results for basin-wide water consumption and GDP are presented in Figure 4.6, as a comparison to the baseline scenario.

The monthly water consumption under the water trading scenario is slightly lower than that under the UWFR scenario (Figure 4.6a). Total water consumption is 33.80 billion m^3 compared to 34.52 billion m^3 under UWFR, while total GDP is higher under the trading scenario (Figure 4.6b). Monthly basin GDP increases particularly during the flood period (July to October). This is because more water is available for trading in this period. The basin-wide GDP under the trading scenario is 1270.1 billion RMB, compared to 1246.7 billion RMB under the UWFR. The GDP for individual trading agents is either greater or equal to that under the UWFR because water trading occurs only when both water seller and water buyer benefit from the transaction.

Figure 4.6—Basin-wide comparisons between the UWFR scenario (baseline) and the water trading scenario (a) monthly water consumption (billion m³); (b) monthly GDP (billion RMB)



Source: This study.

Table 4.1 presents a summary of the difference in water consumption and GDP under the water trading scenario and the baseline (UWFR) for upstream and midstream/downstream agents. It should be noted that the consumption values presented are not equivalent to the volume of water traded. As expected, the upstream agents (Agent 1 to Agent 22) use less water under the water trading scenario compared to the UWFR scenario (about 3.27 billion m^3 annually), while the midstream and downstream agents (Agent 23 to Agent 52) use more (2.55 billion m^3 annually). This confirms that upstream agents tend to sell water to gain revenue and downstream agents tend to buy water for greater water use benefit. The GDP increase is 5.64 billion RMB for upstream agents and 17.8 billion RMB for midstream and downstream agents, with a total annual GDP increase of 23.45 billion RMB. Most of the additional economic benefit, 88 percent, is obtained during the high-flow period (77 percent for upstream agents and 92 percent for midstream/downstream agents). Thus, interestingly, a small reallocation of water in the high-flow season does have a significant value to water-using agents, particularly in the mid- and downstream reaches.

Table 4.1—Differences in water consumption and GDP for upstream and midstream/downstream agents in water trading and UWFR scenario (billion m3 and RMB)

	Water Consumption difference		GDP difference	
Month	Upstream (A1–A22)	Midstream/downstream (A23–A52)	Upstream (A1–A22)	Midstream/Downstream (A23–A52)
1	-0.058	-0.022	0.299	0.162
2	0.001	-0.011	0.088	0.100
3	-0.047	0.021	0.102	0.213
4	-0.086	-0.004	0.089	0.040
5	-0.056	0.070	0.306	0.191
6	-0.100	0.044	0.150	0.073
7	-0.568	0.380	0.904	3.193
8	-0.420	0.262	0.849	1.988
9	-1.137	1.082	1.563	5.924
10	-0.721	0.678	1.076	5.308
11	-0.030	0.005	0.149	0.150
12	-0.054	0.046	0.072	0.461
Sum	**-3.276**	**2.551**	**5.648**	**17.805**

Source: This study.

Table 4.2 presents the actual volume of water bought and sold by upstream and midstream/downstream agents and for the entire basin over 12 months. Again, midstream and downstream agents buy more water, whereas upstream agents sell more water. Moreover, for all months, the quantity of water sold exceeds the quantity of water purchased. The additional water is used to fulfill the ecosystem flow requirements. The government has to buy this amount of water to maintain downstream ecosystem flows given the established ecological flow targets. The total annual value of water transactions, at 2.95 million RMB, is actually quite low compared to the total additional basin-wide GDP increase of 23.45 billion RMB. Thus, water trading is efficient from an economic point of view.

Table 4.2—Water trading (billion m3) and the economic benefit (billion RMB) of water trading

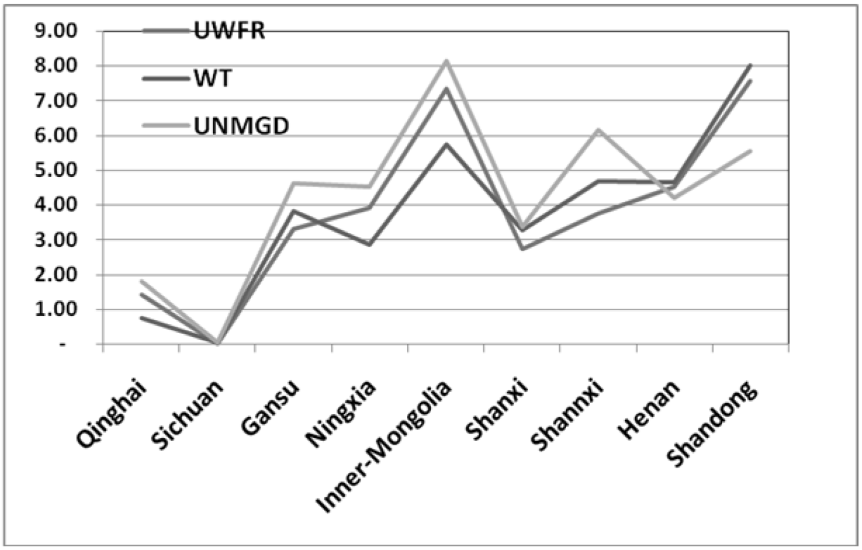
Month	Upstream water purchases	Mid-stream/ downstream water purchases	Upstream water sales	Mid-stream/ downstream water sales	Total water purchases	Total water sales	Difference	Transaction value
1	0.0004	0.0001	0.0674	0.0405	0.0005	0.11	0.11	0.56
2	0.01	0.02	0.03	0.05	0.03	0.08	0.05	0.02
3	0.01	0.05	0.07	0.05	0.06	0.12	0.06	0.06
4	0.01	0.02	0.14	0.05	0.03	0.19	0.16	0.06
5	0.09	0.09	0.47	0.04	0.18	0.51	0.32	0.06
6	0.04	0.07	0.19	0.06	0.12	0.24	0.13	0.02
7	0.08	0.79	0.93	0.66	0.88	1.58	0.71	0.81
8	0.12	0.44	0.99	0.42	0.56	1.41	0.86	0.54
9	0.09	1.41	1.54	0.44	1.50	1.98	0.48	0.42
10	0.06	0.69	0.87	0.09	0.75	0.96	0.21	0.28
11	0.01	0.04	0.15	0.07	0.06	0.21	0.15	0.07
12	0.0005	0.0908	0.0564	0.0610	0.0914	0.12	0.03	0.05
Sum	**0.53**	**3.72**	**5.50**	**2.01**	**4.25**	**7.51**	**3.26**	**2.95**

Source: This study.

The results of the water trading scenario demonstrate that basin-wide water-related GDP can increase significantly under water trading despite strict flow control measures for the downstream ecosystem as enforced by the government since 1999.

Figure 4.7 presents total water consumption results across the basin provinces for the UWFR baseline as well as for the unmanaged and water trading scenarios. Compared to the UWFR, water depletion increases significantly upstream under the unmanaged scenario, which supports maximization of withdrawals upstream. Under UWFR, on the other hand, more water flows downstream for higher-value agricultural withdrawals, particularly in Shandong Province, and to support downstream ecosystem flow requirements. The water trading scenario similarly follows prescribed withdrawals downstream to support the ecosystem agents, but also reallocates water from Inner Mongolia and Ningxia to Shanxi, Shaanxi, and Gansu Provinces.

Figure 4.7—Water consumption in the YRB under alternative allocation scenarios (BCM)



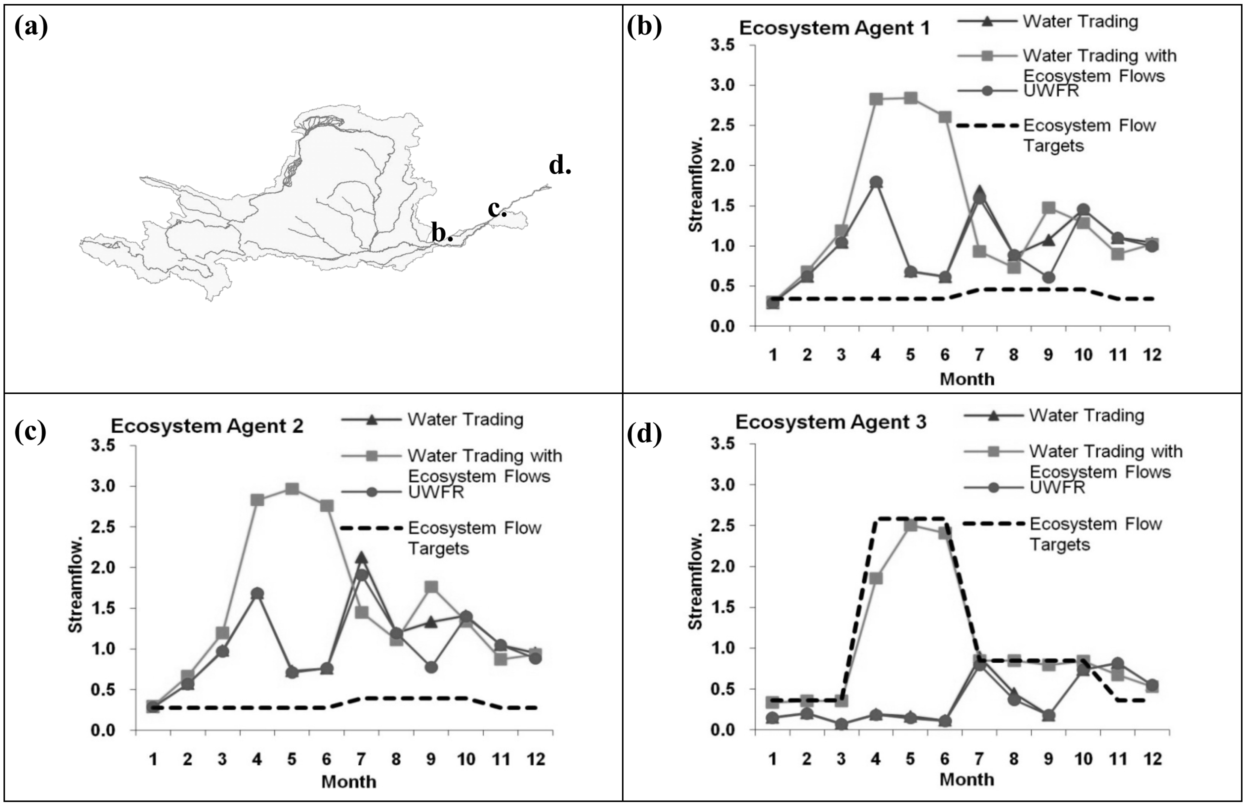
Source: This study.

The Impact of Alternative Ecosystem Flow Requirements

The UWFR was implemented chiefly to restore downstream flows in the YRB to preserve the ecosystem in the delta area. However, several studies suggest flow level requirements that exceed the achievements of the UWFR. In the following, we assess the impact of ecosystem flow requirements suggested in the literature on flow availability and the potential for water trading under these larger downstream ecosystem flow requirements. Instead of the UWFR downstream flows, the values of the instream flow requirements presented in Table 2.1 are used for the agents controlling ecosystem flows downstream. Under this scenario, upstream bargaining between agents cannot result in streamflows below those listed in Table 2.1 (using the values that do not consider sediment flushing). The difference between UWFR values and ecosystem flow target values are shown in Figure 4.8. EA_1 and EA_2 have lower ecosystem flow needs compared to EA_3, where the suggested instream flows for EA_3 in April, May, and June are significantly higher than for other months to sustain the fish breeding period in the bayou area. The initial water prices and the setting of reservoir agents remain the same as discussed above.

Table 4.3 presents the results for basin-wide water trading, and shows that under the higher ecosystem flow requirements water purchases decline to zero for the months of January, April, and June, which means that no one is buying water in the system and that agents consume water equivalent to M&I needs, which reflects the minimum water use of an agent. At the same time, agents sell significant amounts of water to maintain ecosystem flows. Despite these sales, instream flow requirements cannot be fully met in the months of January, where a total of 0.36 billion m^3 is needed, and April and June, where downstream flow needs amount to 2.58 billion m^3 of water. Thus, it is physically impossible to satisfy both human and ecosystem requirements in those months unless additional measures are undertaken, such as reservoir reoperations or new infrastructure development. The total transaction value or costs for the government (third column in Table 4.3) for those three months are computed using the initial water price (27 RMB/m^3). It should be noted that the 27 RMB in these three months are used for calculation purposes only.

Figure 4.8—Ecosystem agent streamflow comparison across the UWFR, the water trading, and the water trading with ecosystem flow scenarios (a) ecosystem agents' locations; (b) streamflows for ecosystem agent 1; (c) streamflows for ecosystem agent 2; (d) streamflows for ecosystem agent 3 (billion m^3)



Source: This study.

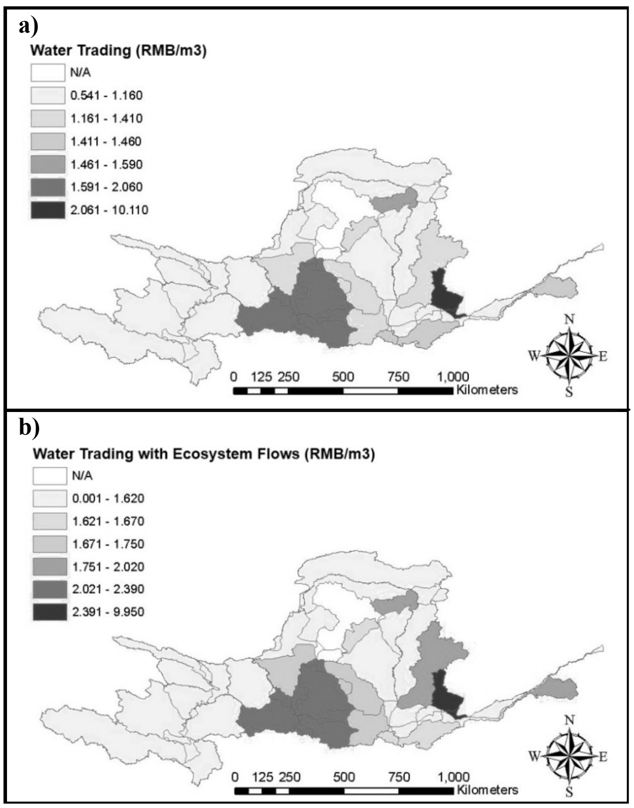
Table 4.3—System-wide water trading and transaction value using suggested ecosystem flow requirements

Month	Total water purchase	Total water sales	Difference	Transaction value
		(billion m^3)		(billion RMB)
1	0.00	0.29	0.29	7.88
2	0.02	0.21	0.20	0.49
3	0.01	0.35	0.35	1.12
4	0.00	1.82	1.82	49.18
5	0.03	2.73	2.70	5.39
6	0.00	2.39	2.39	64.46
7	0.92	1.58	0.65	0.35
8	0.56	1.81	1.25	0.75
9	1.20	2.37	1.17	2.09
10	0.80	1.10	0.30	0.33
11	0.13	0.13	0.00	0.00
12	0.09	0.10	0.01	0.01
Sum	3.76	14.89	11.13	**132.05**

Source: This study.
Note: For exchange rate, see Figure 4.3.

Annual average water prices for the two different ecosystem flow requirement settings are presented in Figure 4.9. Because January, April, and June used the initial water price due to the physical limitation, these three months are excluded from the annual average water price computation. When UWFR flows are used as instream flow targets, the average water price on the mainstream is 1.16 RMB/m^3. If the ecosystems flow requirements follow the published literature, then the average water price on the mainstream increases to 1.62 RMB/m^3. The spatial patterns of Figure 4.9a and 4.9b are very similar, but water prices are about 30 percent higher, on average.

Figure 4.9—Annual average water prices under different ecosystem flow requirements (a) using UWFR results as target flows; (b) using suggested values from previous environmental flow studies presented in Table 2.1



Source: This study.

5. CONCLUSIONS

This paper addresses basin-wide water allocation considering both human and natural water demands using a Multi-Agent System (MAS) model. Decision making for different types of water users with different objective functions located in a river basin context is complex due to spatial heterogeneity, temporal variability, and historical and political considerations. The MAS modeling framework can define each water user and reservoir as active, and ecological zones as reactive agents, and represent the problem mathematically. A penalty-based, decentralized optimization algorithm is applied to solve the problem.

The Yellow River Basin (YRB) in China, a basin with a long history of basin-wide water resources management practices, is used as a case study to demonstrate the real-world functionality of the MAS model, which is formulated and run for several scenarios. The Unified Water Flow Regulation (UWFR) conditions observed in 2000 are used as the baseline for both model calibration and scenario comparison. The calibration process shows a reasonable match between MAS-modeled water consumption and streamflows and the observed values.

Two additional scenarios, one representing water allocation and use prior to the UWFR scenario, the scenario without regulation, and one scenario allowing for water rights trading, are evaluated regarding the impact of different management mechanisms. The scenario without regulation results in higher basin water consumption but lower basin gross domestic product (GDP) compared to the baseline scenario, and flow cutoffs occur in the downstream area of the basin. The water trading scenario, solved by a penalty-based, decentralized optimization algorithm, results in both lower water consumption and higher basin GDP compared to the UWFR scenario. The water trading scenario can improve agents' net benefits as well as overall basin water use efficiency. In this scenario, water prices are determined locally on a monthly basis. Results show significant variation across agents and months. Moreover, we can also calculate the total value of water transactions and compare it to total GDP increase to assess whether basin welfare increases under water trading. The value of water trading would be much higher if municipal and industrial (M&I) use did not receive first priority and thus would become an active water trading sector.

An extended analysis shows the consequences of different ecosystem flow requirements on equilibrium water prices and water trading outcomes. The results indicate that ecosystem flow requirements cannot be fully met for some months in 2000 if all M&I demands in the basin are also to be fulfilled; furthermore, irrigation would have to be significantly curtailed. Thus, the competition between M&I and ecosystem flow demands is expected to increase, and irrigated agriculture will likely be the sector losing water as a result. One way to address this issue would be for reservoir agents to include ecological flow requirements in their operation rules for storage and release.

APPENDIX: THE ALGORITHM TO SOLVE THE MULTI-AGENT SYSTEM MODEL

A modified, penalty-based, decentralized method (İnalhan et al. 2002, Yang et al. 2009) is applied in this study to solve the formulated Multi-Agent System (MAS) mathematical problem. This algorithm allows each agent to have its own decision context that captures both local benefits and the interconnected constraints associated with these benefits. The method achieves optimization among agents under a bargaining scheme, in which the i^{th} agent optimizes its objective with a selected priority for collaboration and sends the solution back to all other agents with which it interacts. The method uses a two-step approach, first finding a solution based on the choices of all individual agents, allowing the violation of some constraints defined with the optimization models for individual agents, and then trying to reduce the constraint violation at the basin level until all constraints are successfully met.

We apply the algorithm to the Yellow River Basin (YRB). We also introduce a management mechanism that assumes the presence of water rights and water rights trading. The mathematical expression for each water user (agent) is:

$$\max F_i(x_i, p_i | w_i) = \max\{f_i(x_i) - p_i(x_i - w_i)\}, \qquad \text{(A1)}$$

where x_i is the water consumption from agent i, $f_i(x_i)$ is the benefit corresponding to x_i consumption, $p_i > 0$ is the local water price applied to agent i, and w_i is water rights or water permit for agent i. Under this setting, $x_i - w_i \neq 0$ can be viewed as the amount of water trading for agent i. When $x_i < w_i$, "$- p_i (x_i - w_i)$" is positive, which means agent i uses less water than it is entitled to. Therefore, "$- p_i (x_i - w_i)$," is the benefit of water selling and works as an incentive to the agent. When $x_i > w_i$, "$- p_i (x_i - w_i)$" is negative and can be interpolated as the cost of water buying for agent i. Applying the first-order condition to equation A1, we can have:

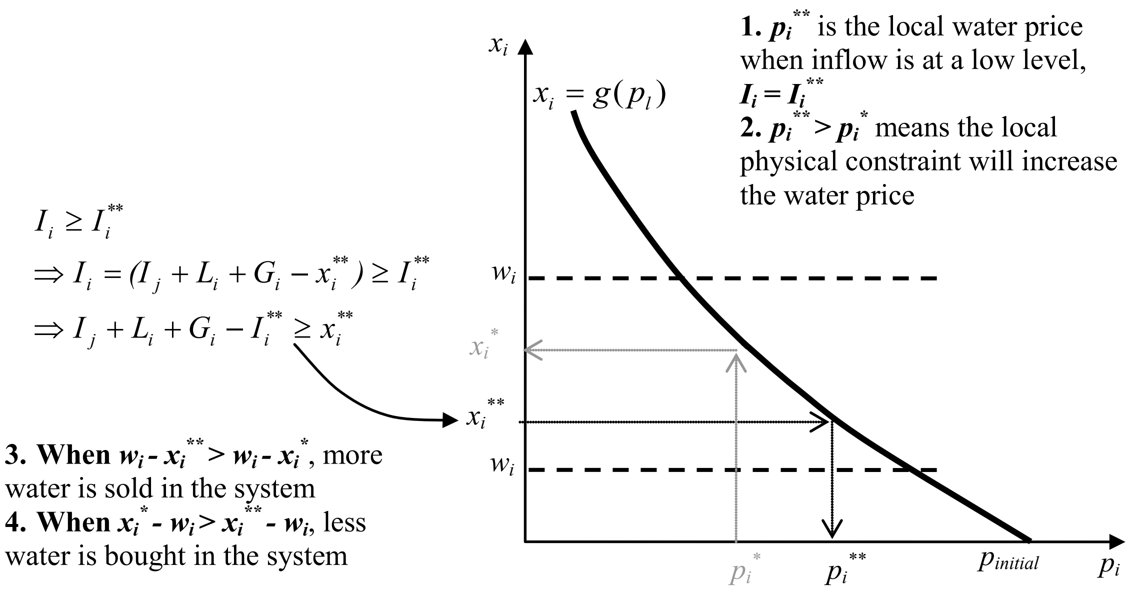
$$\frac{\partial F_i}{\partial x_i} = 0 \Rightarrow f_i'(x_i) - p_i = 0 . \qquad \text{(A2)}$$

It is assumed that each agent will adjust its pi to satisfy equation A2, which means that the marginal benefit equals the local water price and that the ideal converge criteria at the system level match when the condition in equation A2 is satisfied for all agents.

The introduction of a water trading mechanism to the MAS formulation allows for water uses of different agents to bypass the original water permit limits by buying additional use rights (or selling use rights if the predetermined water price is too high to warrant productive activities). The following criteria are set up to ensure that water prices converge at a reasonable level: 1) total water consumption equals less than or the same as total water permits; 2) whenever the outflow from agent i reaches zero, water trading with agent i will stop, which means additional trade is physically impossible even if desired by agents; 3) agents cannot buy water from downstream agents (negative outflow); 4) only water for agricultural uses can be traded; municipal and industrial (M&I) water use is treated as the basic water use rights for all agents and needs to be met before any irrigation demand can be met; and 5) to avoid flow cutoff downstream, minimum flow requirements are set for ecosystem agents equivalent to what has been achieved under the Unified Water Flow Regulation (UWFR) in force since 1999.

Figure A.1 presents the concept to determine converging local prices. Whenever the outflow from an agent i become negative, the water price will stop decreasing for agent i, which means additional trade is physically impossible, even if it is desired by agents. If we put this constraint ($I_i \geq I_i^{**}$, $I_i^{**} = 0$ in our setting) on Figure A.1, it will act as an additional constraint for water consumption, because the outflow from agent i is the result of the water balance equation, and if a constraint is enforced on outflow it will also affect water consumption. Due to this constraint, the water price cannot decrease to the level determined by the market (p_i*), but is constrained at a new equilibrium price (p_i**). Meanwhile, the water price decease for all agents above agent i will also stop at this point. This criterion means that any physically possible water transaction (from upstream to downstream) is allowed, but it is unfeasible for an upstream agent to buy water from a downstream (negative outflow) agent. The water price will converge in this situation. These converged water prices are the equilibrium prices for the maximum amount of water transactions under the physical constraint. Figure A.1 also shows that the new equilibrium prices (p_i**) when the physical constraint is taken into account will be higher than the water price (p_i*) solely based on the market incentive. The marginal benefit of water is higher in this situation. When the water price is maintained at a level higher than p_i*, the total water sold can be larger than the total water bought, which implies that the additional water will be left in the stream to fulfill the environmental flow requirements.

Figure A.1—The convergence of local water price and the consequent agents' water consumption with local streamflow (physical) constraints



Sources: This study.

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